Photometry of two unusual A supergiant systems in the Small Magellanic Cloud

R. E. Mennickent[1]

Departamento de Astronomía, Facultad de Ciencias Físicas y Matemáticas, Universidad de Concepción, Casilla 160-C, Concepción, Chile

rmennick@astro-udec.cl

M. A. Smith

Department of Physics, Catholic University of America, Washington, DC 20064, USA; Present address: Space Telescope Science Institute, 3700 San Martin Dr., Baltimore, MD 21218, USA

Z. Kołaczkowski

Instytut Astronomiczny Uniwersytetu Wroclawskiego, Kopernika 11, 51-622 Wroclaw, Poland

G. Pietrzyński

Warsaw University Observatory, Al. Ujazdowskie 4, 00-478 Warszawa, Poland

and

I. Soszyński

Warsaw University Observatory, Al. Ujazdowskie 4, 00-478 Warszawa, Poland

Received ______________; accepted ______________

Submitted to PASP.

ABSTRACT

We present multiwavelength broadband photometry and V, I time resolved photometry for two variable bright stars in the SMC, OGLE004336.91-732637.7 (SMC-SC3) and OGLE004633.76-731204.3 (SMC-SC4). The light curves span 12 years and show long-term periodicities (SMC-SC3) and modulated eclipses (SMC-SC4) that are discussed in terms of wide-orbit intermediate mass interacting binaries and associated envelopes. SMC-SC3 shows a primary period of 238.1 days along with a complicated waveform suggesting ellipsoidal variablity influenced by an eccentric orbit. This star also shows a secondary variability with an unstable periodicity that has a mean value of 15.3 days. We suggest this could be associated with nonradial pulsations.

Subject headings: stars: early-type – stars: emission-line, Ae – stars: mass-loss – stars: evolution – stars: activity

1. Introduction

The evolution of massive stars is an important topic of stellar astrophysics because it provides clues to the mechanisms that feed the Galactic medium with the building blocks of future generations of stars. Many of the evolutionary stages of massive stars are short-lived and hence challenge our ability to find enough examples of a common group to characterize them. Detecting objects in these brief phases of evolution is of great use in testing current theories of massive star evolution, especially if they represent populations with low metal abundances, a property of stars in the Magellanic Clouds. A complete census of pre- and just post-main sequence population of massive stars in the Clouds has not yet been compiled, and thus attributes of these subpopulations are not well known, but they are known to be generally variable. Catalogs of B stars with unusual variable light curves in the Magellanic Clouds (e.g., Mennickent et al. 2002, hereafter M02 and Sabogal et al. 2005), based on OGLE photometry (Udalski et al. 1997, Szymański 2005), provide excellent material for analysis of massive stars near the main sequence. In an effort to characterize some of these stars, follow up spectroscopy was conducted for two stars in the Type 3 M02 sample[1], that will be given in a future paper (Mennickent & Smith 2010, hereafter MS10). Both these stars turn out to be probable binaries and to have highly peculiar characteristics. In this paper we present the photometric results for these stars.

The stars chosen were taken from an initial sample of 8 Type-3 variables in the M02 catalog satisfying the arbitrary criterion of having visual magnitudes brighter than 14.2. No other criteria were imposed on their selection. The stars selected were OGLE004336.91-732637.7 (≡ SMC-SC3-63371, MACHO ID 213.15560; hereafter SMC-SC3) and OGLE004633.76-731204.3 (≡ SMC-SC4-67145, MACHO ID 212.15735.6;

[1]Type-3 variables are SMC Be star candidates with I-band light curves varying periodically or quasi-periodically.

hereafter SMC-SC4). Exploratory optical spectra exhibited substantial H_α emissions in both objects, and in the case of SMC-SC3, multiperiodic variability (Mennickent et al. 2006, hereafter M06). SMC-SC3 was recently included in the slitless survey of Hα emission line objects by Martayan et al. (2010, their star in cluster SMC-17).

The goals of this paper are to characterize the photometric properties of these two stars with the longer time baseline available and gain further insights on the formation and nature of these systems.

Table 1. $UBVR$ magnitudes from Massey (2002) and OGLE photometry are given. f Dereddened $B-V$ colors and derived spectral types are also included.

Object	U	B	V	R	V_{OGLE}	$(B\text{-}V)_{OGLE}$	$(V\text{-}I)_{OGLE}$	$(B\text{-}V)_0$	Sp. type
SMC-SC3	-	13.63	13.48	13.30	14.18	0.181	0.331	0.08	A4
SMC-SC4	14.34	14.15	13.94	13.70	14.06	0.206	0.385	0.11	A5

Table 2. Infrared magnitudes for program stars. Phases refers to ephemeris given in Equations 1 and 4.

Object	I	J	H	K	JD/Date	Phase	Source
SMC-SC3	13.701(9)	13.346(22)	-	12.954(116)	1998-08-12	0.52	cds.u-strasbg.fr/denis.html
SMC-SC3	13.847(30)	13.472(90)	-	13.050(180)	2450414.6148	0.90	cds.u-strasbg.fr/denis.html
SMC-SC3	13.781(40)	13.560(110)	-	13.134(160)	2451048.7763	0.56	cds.u-strasbg.fr/denis.html
SMC-SC3	-	13.545(42)	13.341(50)	13.275(40)	2451034.7109	0.50	www.ipac.caltech.edu/2mass/
SMC-SC3	-	13.540(20)	13.380(10)	13.180(20)	-	-	pasj.asj.or.jp/v59/n3/590315/
SMC-SC4	13.655(30)	13.388(90)	-	13.316(210)	2450418.5524	0.42	cds.u-strasbg.fr/denis.html
SMC-SC4	13.616(30)	13.383(130)	-	13.079(150)	2451039.7991	0.79	cds.u-strasbg.fr/denis.html
SMC-SC4	-	13.403(29)	13.236(34)	13.054(35)	2451034.7134	0.76	www.ipac.caltech.edu/2mass/
SMC-SC4	-	13.380(10)	13.260(10)	13.170(20)	-	-	pasj.asj.or.jp/v59/n3/590315/

2. Photometric results

We give broad-band V and V_{OGLE} magnitudes and $UBVR$ colors for both program stars in Table 1, along with dereddened colors $(B-V)_0$ and estimated spectral types. For SMC-SC3, we calculated $(B-V)_0$ using $E(B-V)$= 0.10 (Martayan et al. 2010). For SMC-SC4, we assumed $E(B-V)$= 0.09 as representative for SMC (van den Bergh 2000). The spectral types listed in Table 1 were derived from $(B-V)_0$ using the Fitzgerald (1970) calibration and assuming a luminosity class of II or I, derived from their magnitudes and membership in the SMC. The $(B-V)_0$ color suggests middle A spectral types. The previous spectroscopic classification of A7-F5 e for SMC-SC3 and F5 Ie+G0 I for SMC-SC4 given by M06 was probably influenced by the detection of shell metallic lines in low resolution spectra, that are formed in relatively cool stellar envelopes.

From the visual magnitudes and SMC distance (Udalski 2000), we can estimate the absolute magnitude as M_V = -4.83 for SMC-SC3 and -5.05 for SMC-SC4. Note that this refers to the visual magnitude of the primary since the secondary contributes only a few percent to the light in this region. Using a bolometric correction of -0.13 for a A5 supergiant, we obtain M_{bol} = -5.0 and -5.2. From the evolutionary tracks for stars with SMC metallicities by Meynet & Maeder (2001, hereafter MM01), both stars fit tracks of 9 $M_{\odot}$ evolved stars in the MM01 models. As the evolutionary tracks of MM01 depend on the value of stellar mass and rotation velocity, the position of the optical component of these systems in the $M_V - T_{eff}$ diagram cannot be used with their models to alone determine the evolutionary state.

SMC-SC3 is a probable member of the open cluster NGC 242, and in fact its angular distance from the cluster center is only $\sim$ 10". In Figure 1 we show the color-magnitude diagram for SMC-SC3 and for neighboring stars present in their field. We investigated the light curves for the stars labelled 1, 2 and 3, and we found them to be photometrically

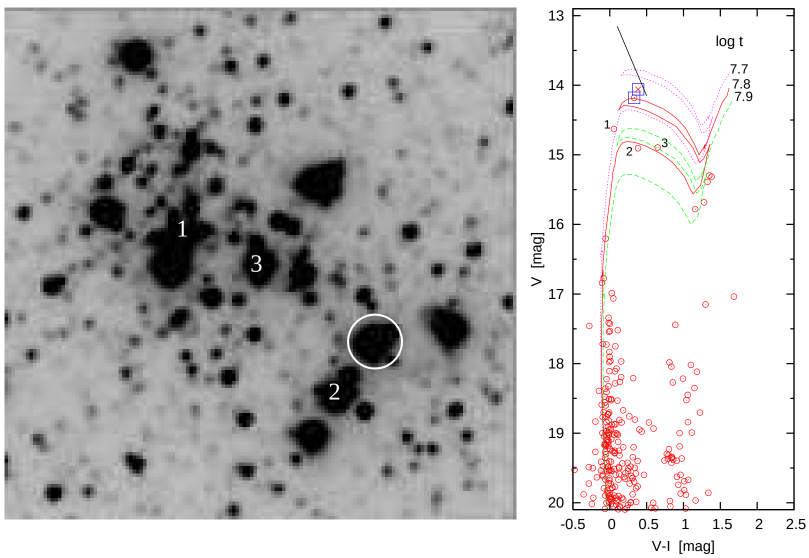

Fig. 1.— The left image is a finding chart of SMC-SC3 centered on the cluster NGC 242 (1' × 1' subframe of the reference I-band image from the OGLE-II survey). North is up and East left. The position of SMC-SC3 is given by a circle and three reference stars are labeled with numbers. Right panel shows the CMD for the same region. The CMD is based on the OGLE II standard VI photometry in the SMC (Udalski et al. 1998a). Three isochrones are also presented (Bertelli et al. 1994) for stars with metallicity Z= 0.004 and ages ($\log t$) labeled in the picture. We adopted these isochrones using $V - M_v$= 19.0, $E(V-I)$= 0.08 and $A_v = 2.5 * E(V-I)$. The reddening vector is indicated by the upper oblique line. For comparison we indicate SMC-S04 with a cross in an open square at the upper right of the SMC-SC3 position.

constant. The figure also depicts isochrones for the cluster NGC 242 considering the parameters given in the figure caption. It is clear that the bright objects represented here lie close to the log t = 7.8 isochrone. This is approximately the reported age of this cluster (7.9; Ahumada et al. 2002). Fig. 1 also depicts the observed position of SMC-SC3. Its unreddened location in the HR Diagram should be projected back along the indicated reddening vector. The position of both objects in the HR Diagram indicates that they are evolved luminous stars found in a stage during core hydrogen exhaustion.

The 2MASS $J-K$ photometry of these two stars is minimally affected by interstellar reddening. These values are 0.27 and 0.35 for SMC-SC3 and SMC-SC4, respectively (Table 2), much larger than the typical $J-K$ color of an A5 supergiant (0.12 mag, Koornneef 1983), as inferred from the $(B-V)_0$. Similarly the $V-K$ colors, of about 0.5 and 0.8 mag, are much larger than the typical $V-K$ color of an A5 supergiant (0.36 mag, Koornneef 1983). Emission caused by scattering of free electrons in circumstellar envelopes is a likely candidate for explaining the infrared excess. Their moderate value excludes the presence of much dust around these stars and explains the discrepancy between spectral types derived from optical and infrared photometric colors.

Deep exposures of sky images surrounding the two program objects reveal no suggestion of nebulosity. However, during our investigation we discovered that SMC-SC3 has a visual companion, the small bump 1” NW of SMC-SC3 in Fig. 1. We analyzed its OGLE light curve as part of this study and discovered that this visual companion is an eclipsing binary with an orbital period of 2.96934 days, V= 16.776, and $V-I$= -0.083. Its ΔI range of variability range was 0.77 mag. This nearby star is not in the catalog of SMC eclipsing binaries (Bayne et al. 2002) but was included in the catalog of eclipsing variables by Udalski et al. (1998b) under designation SMC-SC3 star number 63551. The fact that the star is 2.6 mag fainter than SMC-SC3 makes it unlikely that the periodicities discussed below are

caused by the contribution of this star's light to the photometric colors.

We have included the following datasets in our analysis: OGLE-II "DoPhot" V light curves, OGLE-II "DIA" I light curves and OGLE-III "DIA" V, I light curves. A summary of these datasets is given in Table 3. The range of HJDs shown corresponds roughly from mid 1997 to mid 2009.

We proceed to analyze the photometric variations in our time series, using the *pdm* (after the Phase Dispersion Minimization algorithm; Stellingwerf 1978).

2.1. Characterization of the light curve of SMC-SC3

The expanded dataset allowed us to examine the possible range of periods over a greater range than was available to M02 and M06. In fact, we found a more reliable primary period that is twice as long as these authors had found, namely 238.1 (+2.3,-3.1) days, but it clearly gives the deeper minimum in the PDM periodogram. The new baseline in time is sufficient to rule out a yet longer (e.g., 476 day) period. The period error is the $HWHM$ of the (asymmetrical) periodogram's peak. The improved ephemeris for the measured centroid of the light curve maximum of SMC-SC3 is:

$$T(HJD) = 2\,450\,915.3 + 238.1(+2.3, -3.1)\,E. \tag{1}$$

We modeled the SMC-SC3 light curve with harmonics and subharmonics of this fundamental period and, after analyzing residuals, it was clear that, apart from a small seasonal variability, the second periodicity of 15-days, reported by M06, still persisted in the Fourier spectrogram (Fig. 3). For this sinusoidal 15 day periodicity we found the ephemeris:

$$T(HJD) = 2\,452\,739.76 + 15.35(0.02)\,E. \tag{2}$$

Table 3. Summary of photometric data analyzed in this paper. HJD zero point is 2400000. OGLE 1, 2 & 3 data are considered.

Object	Dataset	HJD-start	HJD-end	N-obs
SMC-SC3	OGLE I-band	50621.83606	54866.55206	1022
SMC-SC3	OGLE V-band	50670.89064	54792.59219	82
SMC-SC4	OGLE I-band	50621.79700	54954.88836	1067
SMC-SC4	OGLE V-band	50645.91866	54954.89402	94

The Fourier periodogram of SMC-SC3 indicates that sidelobes surround the primary peak. This fact suggests the possibility that the Fourier spectrum shows the combined effect of several close frequencies acting simultaneously giving origin to harmonic interactions. However, in this case we should observe a modulation of the amplitude of the light curve, and this is not observed in our reconstruction of the 15-day light curve. Another interpretation for the existence of sidelobes comes from the analysis of the O-C diagram (based on observed minus calculated ephemeris, e.g. Sterken 2005), that can be used as a diagnostic for a constant 15-days signal (Fig. 4.) The O-C diagram should display the differences between predicted and observed phases from cycle to cycle as following a horizontal or sloped line if the variable had a constant period. On the contrary, most of the data points in Fig. 4 follow a regular oscillation for the 15-day period - that is they suggest a single period that varies over time. The period changes around a mean value on a timescale of $\approx$ 3800 days.

In order to test the possibility that the sidelobes observed in the Fourier spectrum of the residual light curve indeed arise from a slowly changing period we constructed synthetic light curves represented by a slow oscillation around 15 days with "superperiod" of 3800 days, viz. :

$$I = 13.84 + A\sin\left(\frac{2\pi t}{15.32 + B\sin(2\pi t/3800)}\right) , \tag{3}$$

where t is the observing time in days and A, B constants to be adjusted to the observations, typically 0.02 mag and 0.15 days, respectively.

The corresponding Fourier spectra showed two sidelobes around the main frequency, suggesting in fact that the Fourier spectrum of residual light in SMC-SC3 is consistent with a variable period. The general appearance of the observed O-C diagram was also

reproduced by our simulation. However, we emphasis that this representation, including the persistence of a 3800-day superperiod, has no predictive power for new additions to this star's light curve.

In the following, and only as a matter of convenience for the analysis, we will consider this complex variability as the simple periodicity represented by the ephemeris given in Eq. 2.

Whereas the 15-day cycle is represented roughly by sinusoidal variability, the 238 days periodicity is characterized by two unequal minima, like those observed in ellipsoidal variables (Fig. 5). However SMC-SC3 does not appears to be a bonafide ellipsoidal variable. The maximum of its light curve is a sharp excursion over a longer asymmetrical variation and the first rising branch is steeper and shorter than the second one. All these features, especially the double modulation and the two unequal minima not separated by half a cycle, are consistent with ellipsoidal variations in an atypical *eccentric-binary* (Hilditch 2001).

2.2. Characterization of the light curve of SMC-SC4

The light curve of SMC-SC4 is of interest in that it not only produces eclipses but the eclipse depths can vary from cycle to cycle (Fig. 2). The ephemeris for the eclipses is:

$$T_{min}(HJD) = 2\,450\,709.9(2) + 184.26(1.25)\,E, \tag{4}$$

where we used the *pdm* algorithm on the expanded I-band dataset to search for periods. From the median of the absolute values of the differences between magnitudes of point to point measurements we estimate a characteristic noise of 0.01 mag for the SMC-SC4 light curve. However, the variability actually observed in the light curve indicates that

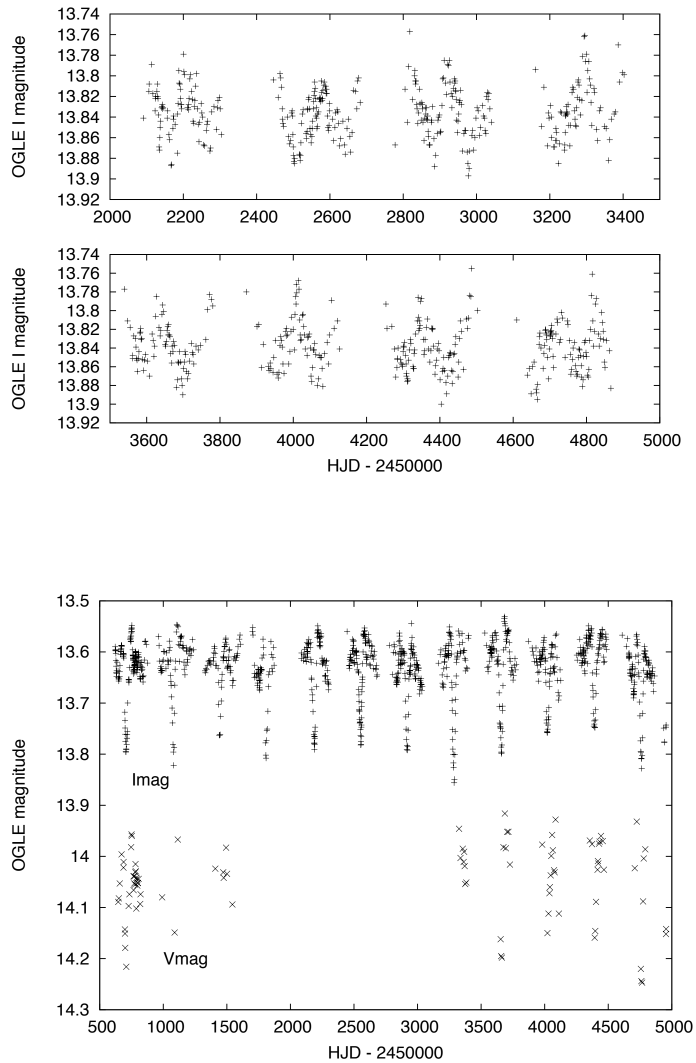

Fig. 2.— OGLE I-band light curve of SMC-SC3 (up) and SMC-SC4 (below). Typical formal error is 0.004 mag.

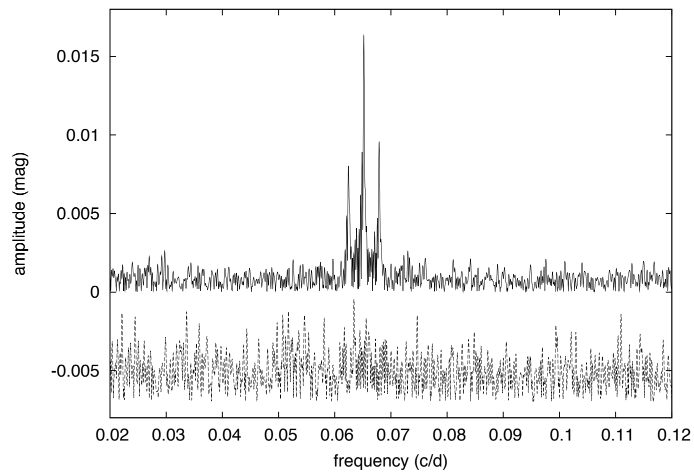

Fig. 3.— Fourier spectrum of such a residual light curve along with the scaled and vertically shifted window spectrum. The main peak is the 15-days periodicity.

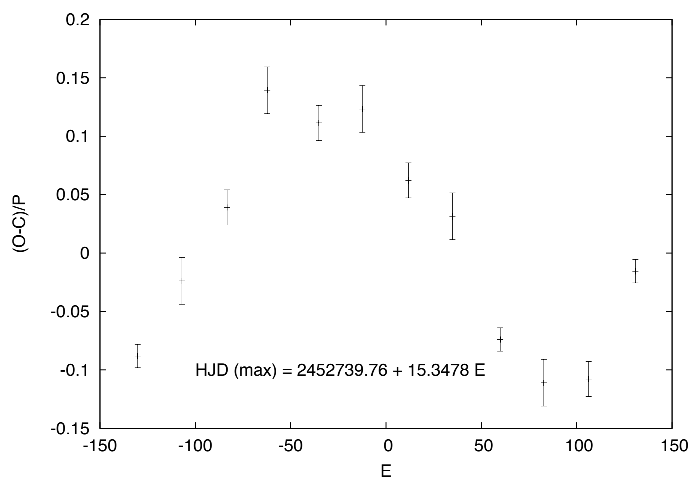

Fig. 4.— O-C diagram for the maxima of the 15-d periodicity of SMC-SC3. This figure shows a time scale of variability for the 15-days cycle of 3800 days, corresponding to twice the distance between maximum and minimum (about 250 cycles).

the variability discussed here is a signal from the star. The new analysis also shows that the former 24-day periodicity reported by M06 was the result of their time-limited dataset and the presence in the light curve of non-coherent quasiperiodic modulations, perhaps pulsations. This signal is responsible for the large noise visible in the smoothed curves of Fig. 6a, particularly outside the primary eclipse. This signal also illustrates the absence of a secondary eclipse in the I-band. The V-band, however, suggests the presence of a very wide secondary eclipse (Fig. 6b). Furthermore, we conclude from this figure that the eclipses are irregular in shape and depth, although they recur with a *mean* period of 184 days. They are about as deep in V as in I, 0.5-0.6 magnitudes. Changes in the eclipse shapes and depths occur and these last appear to be modulated. For instance, OGLE III data suggest a supercycle for the eclipse depth of about eight times the basic period, but this tendency disappears when considering the earlier OGLE II dataset (i.e., those obtained before HJD 2452000, Fig. 2). We argue that the same low frequency variability observed outside eclipse could be responsible for the observed changes in eclipse shape, but not for the depth changes.

3. Discussion

In this section we will evaluate the interesting attributes of SMC-SC4 light curve first, and then follow with a discussion on the even more remarkable properties of SMC-SC3.

The fact that eclipses of SMC-SC4 are irregular in depth but with an arguably regular timing indeed indicates that the A star is eclipsed by an almost opaque but possibly ever changing body, rather than by the secondary star. There are at least two additional reasons that the eclipse cannot reasonably be ascribed to a star-star eclipse:

i) a large fraction of the A star is eclipsed, and if they were caused by the much hotter star

(such as we observe in the near-UV, see MS10) the eclipse depths would be larger in the V magnitude than in I,

ii) the radius of the secondary star is likely to be smaller than the A star's and cannot account for the large geometric obscuration observed in the I band, yet the long ($\sim$0.2 cycles) duration of the eclipse implies that a large body orbits near the A star. This body is warm (accounting for the nearly equal eclipse depths in the two photometric bands) and is therefore likely to be within a stellar radius or so from the A star.

We conclude that that the eclipses are inconsistent with a third star in a dynamically stable orbit. Rather they are caused by a large almost opaque body probably extending well out of the orbital plane of the SMC-SC4 system and intruding to our line of sight during this phase. It appears to be due to an impermanent, ever-replenished structure that co-orbits within the binary star system.

The photometric variability of SMC-SC3 analyzed in this paper consisting of a main ellipsoidal variability is consistent with a binary nature. As mentioned earlier, the double minima of the 238-day folded light curve exhibit unusual signatures which can be interpreted only in terms of an ellipsoidal variable. The unequal amplitudes, spacings, and asymmetries of the minimum lobes strongly suggest that this object is a binary with a mild eccentricity. Model light curve grids of Soszyński et al. (2004) suggest that the asymmetry of especially the time of second minimum is sensitive to a large orbital eccentricity. A comparison of these models imply that the orbital eccentricity is nonzero but modest, e.g. $e \approx 0.2$. However, another diagnostic argues that any eccentricity in this system is actually somewhat larger. In particular, the sharp maximum observed for SMC-SC3 at phase 0.0 (Fig. 5) is not typical of small eccentricities, but examples have been well documented. For example, a similar feature has been observed, but much less pronounced, in V380 Cygni (Guinan et al. 2000, see other examples in Fig. 8 of Soszyński et al. 2004).

These maxima are frequently interpreted as the reflection of the more hotter star on the distorted and more distended cooler star at minimum binary separation. According to canonical interpretations of ellipsoidal variable light curves, the light maximum corresponds to a time when the visible star (in this case, the secondary at optical wavelengths) presents its maximum area in the plane of the sky. The fact that we see evidence in the form of an absolute light maximum at this same phase indicates that this phase corresponds nearly to periastron passage as well. Although this places some geometrical constraints on the orbital parameters, it is clear that a precise determination of the orbital parameters requires a set of RVs sampling the whole binary cycle. Most importantly, given a period as long as 238 days, the semimajor axis of the orbit must be large, and this, together with the presence of a reflection effect suggests that the eccentricity is large, perhaps $e \approx 0.9$.

We are not yet able to reconcile these considerations, but we have a preference currently for the high eccentricity because we believe the "reflection effect" is the more robust interpretation.

We note the similarity of the photometric behavior of our targets with the recently released light curves of OGLE-LMC-LPV-41682, that with V= 13.958 shows eclipses of variable depth with period 219.9 days, and a second periodicity of 44 days, and possibly OGLE-LMC-LPV-15046, that with V= 16.887 shows a main period of 148.67 days, along with lower amplitude periods of 272.60 and 181.88 days, resulting in a light curve with oscillations of variable amplitude (Soszyński et al. 2009). This opens the possibility that SMC-SC3 and SMC-SC4 are not rarities and can be understood within the context of luminous interactive binaries in which mass loss and/or exchange may be occurring. These objects will be discussed in a forthcoming paper.

Regarding the short photometric cycles observed in both systems, (15-days cycle in SMC-SC3 and otherwise still unspecified non-coherent variations in SMC-SC4) we consider

the possibility that they could be linked to nonradial pulsations of the A supergiant. The variability of the 15-day photometric cycle observed in SMC-SC3 suggests a non-binary nature. It is generally believed that hot and luminous stars of the α-Cygni type show irregular variability driven by nonradial pulsations on time scales of weeks (e.g., de Jager et al. 1991). These are supergiants of spectral types B-A and amplitude of variability $\sim$ 0.1 mag. It is then possible that part of the photometric variability observed in our program objects corresponds to pulsational activity. The amplitude of these pulsations in SMC-SC4 is large enough that we suspect that even partial eclipses of the A-type supergiant allows their detection.

We considered also the possibility that the 15-day cycle corresponds to advection of stellar spots. However, for $v\, sin\, i$= 20 $\pm$ 5 km/s and R= 30 $R_{\odot}$ derived by MS10, the rotational period of the A supergiant should be 76 sin i days. This is too long to fit the 15-day periodicity and, assuming that its orientation is not nearly pole-on, not synchronous with the binary period.

4. Conclusions

We have presented the analysis of OGLE light curves of two SMC bright systems showing novel photometric properties. These properties are consistent with the interpretation that these stars are long-period interacting binaries with an evolved most-luminous stellar component. We find eclipses in SMC-SC4 with P_o= 184 days modulated in depth and perhaps shape on time scales of hundreds of days, suggesting the presence of a variable and non-stellar eclipsing region. In addition, we discovered an unusually strong reflection effect in the orbital light curve of SMC-SC3 (P_o= 238 days) and a short variability with quasi-period 15.3 days changing on time scales of 3800 days. We note the possibility that the short-term fluctuations observed in both stars are signatures of nonradial pulsation.

This may explain the "drifting" of a single 15-day periodicity in the light curve of SMC-SC3.

We thank an anonymous referee for a rapid review and useful indications that improved an earlier version of this paper. REM acknowledges support by Fondecyt grant 1070705, the Chilean Center for Astrophysics FONDAP 15010003 and from the BASAL Centro de Astrofísica y Tecnologias Afines (CATA) PFB–06/2007. We thank Dr. Darek Graczyk for discussions about the reflection effect observed in SMC-SC3.

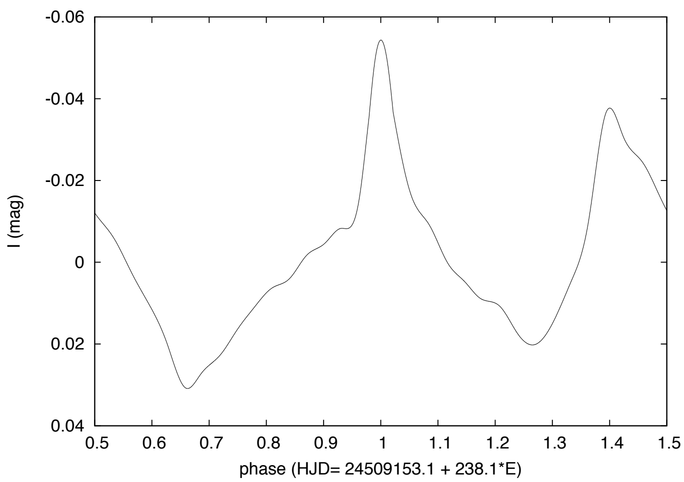

Fig. 5.— The spline function representing the ellipsoidal variability of SMC-SC3 folded over a period of 238.1 days. Spectra to be discussed in M10 are at phases 0.28, 0.69 and 0.44.

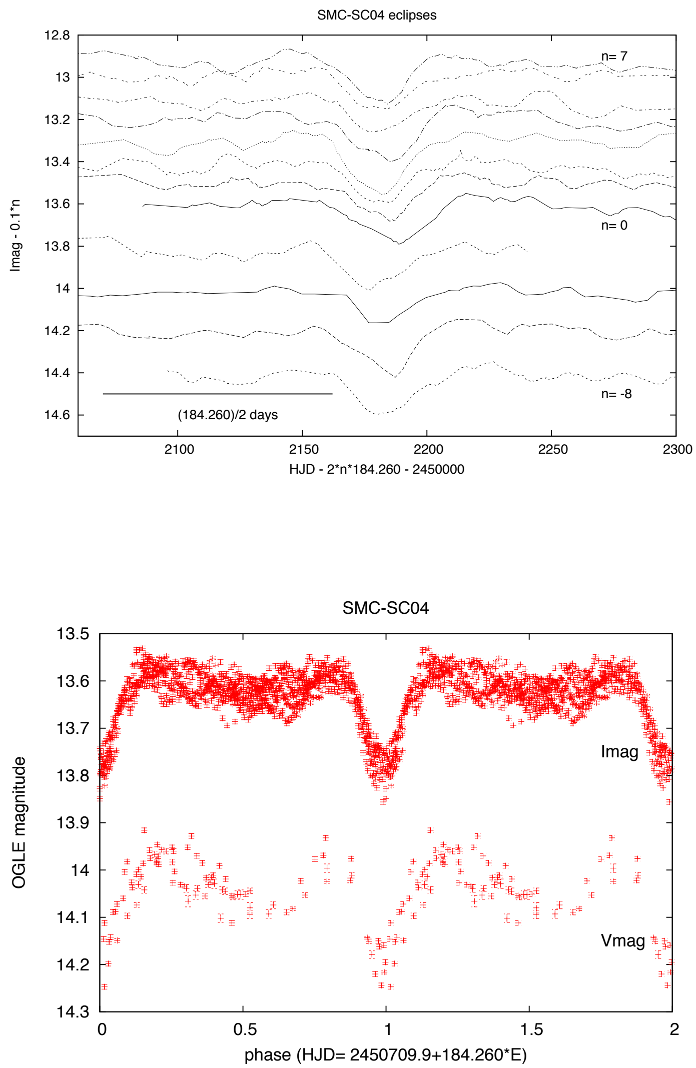

Fig. 6.— Coplotting of eclipses in SMC-SC4 (upper panel). The factor "2" in the x-axis label accounts for the data seasonal gaps. The star was observed annually at the same time of year, and one season happens to be roughly twice the orbital period of the star. Light curves for I and V filter OGLE data are folded with the ephemerides given in equation 2 of the text, i.e. with the period of 184.25 days (bottom panel). The V band data were taken over part of the longer timespan of the I band observations. Note that the eclipse minima in V are at least as deep as for the I filter. Spectra to be discussed in M10 are at phases 0.10, 0.23 and 0.66.

REFERENCES

Ahumada A. V., Clariá J. J., Bica E., Dutra C. M., 2002, A&A, 393, 855

Alcock C., et al., 1993, Natur, 365, 621

Bayne G., et al., 2002, yCat, 833, 10609

Bertelli G., Bressan A., Chiosi C., Fagotto F., Nasi E., 1994, A&AS, 106, 275

Fitzgerald M. P., 1970, A&A, 4, 234

Guinan E. F., Ribas I., Fitzpatrick E. L., Giménez Á., Jordi C., McCook G. P., Popper D. M., 2000, ApJ, 544, 409

Hilditch R. W., 2001, An Introduction to Close Binary Stars, Cambridge University Press

de Jager, C., de Koter, A., et al. 1991, A&A, 244, 131

Koornneef J., 1983, A&A, 128, 84

Martayan C., Baade D., Fabregat J., 2010, A&A, 509, A11

Massey P., 2002, ApJS, 141, 81

Mennickent, R. E., Pietrzyński, G., Gieren, W., et al. 2002, A&A, 393, 887

Mennickent R. E., Pietrzyński G., Diaz M., Gieren W., 2003, A&A, 399, L47

Mennickent, R. E., Cidale, L., Pietrzyński, G., et al. 2006, A&A, 457, 949 (M06)

Mennickent R. E., Smith M., MNRAS submitted (MS10).

Meynet G., Maeder A., 2001, A&A, 373, 555

Sabogal B. E., Mennickent R. E., Pietrzyński G., Gieren W., 2005, MNRAS, 361, 1055

Sterken C., 2005, in "The Light-Time Effect in Astrophysics: Causes and cures of the O-C diagram", ASPC, 335, 3

Soszynski I., et al., 2004, AcA, 54, 347

Soszyński I., et al., 2009, AcA, 59, 239

Stellingwerf R. F., 1978, ApJ, 224, 953

Udalski A., 2000, AcA, 50, 279

Udalski A., Kubiak M., Szymański M., 1997, AcA, 47, 319

Udalski A., Szymanski M., Kubiak M., Pietrzyński G., Wozniak P., Zebrun K., 1998a, ActA, 48, 147

Udalski A., Soszyński I., Szymanski M., Kubiak M., Pietrzyński G., Wozniak P., Zebrun K., 1998b, AcA, 48, 563

van den Bergh S., 2000, The galaxies of the Local Group, by Sidney Van den Bergh. Published by Cambridge, UK: Cambridge University Press, 2000

Schiller, F., & Przybilla, N. 2008, A&A, 479, 849

Szymański M., 2005, AcA, 55, 43

This manuscript was prepared with the AAS LaTeX macros v5.2.